GaAs/AlGaAs multiquantum well resonant photorefractive devices fabricated using epitaxial lift-off

C. S. Kyono, K. Ikossi-Anastasiou,[a)] W. S. Rabinovich, S. R. Bowman, and D. S. Katzer
Naval Research Laboratory, Washington, DC 20375

A. J. Tsao[b)]
The University of Texas at Austin, Austin, Texas 78712

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This letter deals with resonant photorefractive devices fabricated from multiquantum wells of $GaAs/Al_{0.3}Ga_{0.7}As$ and operated in a quantum-confined Stark effect geometry. Details of the processing are presented. Epitaxial lift-off was used to remove the active device from the substrate. Low-temperature $Al_{0.3}Ga_{.07}As$ was used as an insulator to form metal-insulator-semiconductor structures on both sides of the multiquantum wells. Proton implant damage was used to improve the fringe visibility. Photorefractive wave mixing with a diffraction efficiency of ~0.03% was demonstrated. The incorporation of a nitride layer between the top electrode and the low-temperature AlGaAs increased the efficiency to 0.5%. The improvement is attributed to a reduction in the conduction of carriers across the low-temperature layer into the electrode.

Resonant photorefractive phenomena are of interest for their nonlinear, electro-optic properties.[1–5] Quantum-confined excitons in multiquantum well (MQW) semiconductor layers give rise to large electro-optic and nonlinear optical effects at room temperature.[6,7] This makes MQW devices well suited for use in a variety of electro-optic signal-processing applications. Photorefractive effects are introduced by the application of an external electric field. The orientation of the field with respect to the MQW determines the nature of the resonant photorefractive effect. The Franz–Keldysh effect (FKE) occurs for a parallel field, and the quantum-confined Stark effect (QCSE)[8] occurs for a perpendicular field. The QCSE produces larger resonant photorefractive effects[9] and higher diffraction efficiencies.[4] Furthermore, shorter carrier transit distances in a QCSE device gives rise to faster response times.[5] In a QCSE structure, the MQW is sandwiched between dielectric layers. A diffraction pattern is formed across the device from coherently interfering laser beams. In the high-intensity regions, the photogenerated carriers drift and become trapped at the dielectric/MQW interface, thereby screening the externally applied field.[5] The optical diffraction grating is recorded as an internal space-charge field variation, which in turn modifies the absorption and the refractive index across the structure.[5]

In this work, epitaxial lift-off (ELO)[10] is implemented for the first time in the fabrication of a GaAs/AlGaAs MQW, resonant photorefractive device in a QCSE configuration. In a photorefractive structure, the GaAs substrate must be removed because it is not transparent to the read/write laser radiation. Standard substrate thinning techniques, which use a combination of mechanical lapping and chemical etching, can lead to uneven material removal and nonuniform optical absorption across the MQW. To avoid this problem, ELO is employed to transfer the MQW thin film from its substrate to an optically transparent support. Conventional dielectric layers were replaced by low-temperature (LT) AlGaAs to simplify the fabrication. Low-temperature AlGaAs has been shown to possess extremely high resistivities following a high-temperature anneal [$\rho \sim 6\times10^{11}$ Ω cm for LT $Al_{0.3}Ga_{0.7}As$ (Ref. 11)]. Finally, ion implantation was performed to reduce lateral carrier diffusion and hence improve the fringe visibility of the grating.[5] Only one or two implants are typically used to make the MQW semi-insulating.[2–5] However, a nonplanar trap profile will influence the charge storage process during the photorefractive process, so in this work six implants were used to minimize this effect.

The layer structure, beginning from the semi-insulating (100) GaAs substrate, is as follows: 250 nm GaAs, 50 nm AlAs, 30 nm LT $Al_{0.3}Ga_{0.7}As$, 3.5 nm GaAs/10 nm $Al_{0.3}Ga_{0.7}As$ (75 periods), and 30 nm LT $Al_{0.3}Ga_{0.7}As$. The layers were not intentionally doped. The structure was grown by molecular beam epitaxy (MBE) at 580 °C with the exception of the LT AlGaAs layers, which were grown at 250 °C. At the end of the growth, the wafer was annealed at 580 °C for 30 min in the MBE chamber. This was done to convert the LT layers into high-resistivity material. A second structure was grown for use in identifying an appropriate implantation sequence for the photorefractive device layers. The test structure is comprised of a 60 period, 7.5 nm GaAs/10 nm $Al_{0.3}Ga_{0.7}As$ MQW, surrounded by conventional $Al_{0.3}Ga_{0.7}As$ buffer layers.

Proton implants were performed at energies of 15, 30, 50, 100, 200, and 280 keV with fluences of 0.08, 0.1, 0.5, 1, 2, and $3\times10^{(\gamma+9)}$ cm^{-2}, respectively. The values of γ examined were 1, 2, 3, and 4; resulting in proton concentrations of 4×10^{14}, 4×10^{15}, 4×10^{16}, and 4×10^{17} cm^{-3}, respectively. After each implant series, the MQW absorption spectrum was measured. The exciton absorption spectra were unaffected by both the $\gamma=1$ and 2 series. A slight reduction in the absorption peak amplitudes was observed after the $\gamma=3$ series, while significant amplitude reduction and linewidth broadening occurred after the $\gamma=4$ series, as shown in Fig. 1.

a)Permanent address: Louisiana State University, Baton Rouge, LA 70803.
b)Present address: Texas Instruments Inc., Dallas TX 75265.

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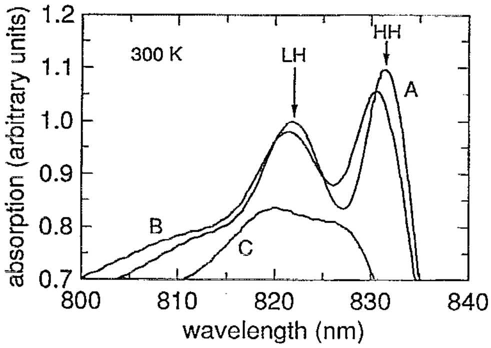

FIG. 1. Absorption spectra for the MQW test structure. Curve A is the spectra before implantation, curve B after the $\gamma=3$ implant series, and curve C after the $\gamma=4$ implant series.

Based on these results, the $\gamma=3$ series was used on the device layers.

A Pd:Au (2 nm: 8 nm) metallization was deposited onto the device wafer after implantation. The sample was covered by Apiezon-W wax and immersed into a $HF:H_2O$ (1:10) solution, maintained near 0 °C to allow slow, selective removal of the AlAs layer.[12] The ELO-separated MQW film area was $\sim 0.6\ cm^2$. A de-ionized water bath provided a particulate-free environment[13] for bonding of the film to a sapphire disk, partially covered with a Cr:Au:Pd (1 nm: 1 nm: 8 nm) metallization. Upon contact, a solid-phase reaction between the Pd and the bottom LT AlGaAs layer firmly bonds the film to the sapphire.[13] The Cr:Au:Pd layer also serves as the backside device contact. A uniform pressure of 3.5×10^4 Pa was applied across the sample using a vacuum-bag apparatus,[14] and the sample was baked overnight at 35 °C. The final device structure is shown schematically in Fig. 2.

The absorption spectra for the photorefractive device displayed light-hole (LH) and heavy-hole (HH) exciton peaks at wavelengths of 843 and 850 nm, respectively. A 10% change in absorption was measured for a ±4 V, 1-kHz square-wave signal. The exciton peaks shift to longer wavelengths with the application of the bias, a clear indication of the QCSE. Photorefractive wave mixing was studied using a cw titanium-sapphire laser in a two beam pump/probe configuration similar to that described in Ref. 15. The interference of two equal intensity 850-nm beams produced a 40-μm period grating in the MQW device. Transient diffraction of these beams occurred when a ±5-V square-wave signal was applied across the device. The diffraction efficiency η is determined from the ratio of the first-order diffracted beam and the transmitted pump beam intensities. An η of ~0.03% was measured as shown in Fig. 3. To the best of our knowledge, this is the first result reported for an ion implanted GaAs/AlGaAs MQW device in a QCSE configuration. Ion implanted $GaAs/Al_{0.3}Ga_{0.7}As$ MQW structures in a FKE configuration have shown η's of up to 0.02%.[3] An η of 3% has been reported for QCSE geometry, Cr-doped, $GaAs/Al_{0.29}Ga_{0.71}As$ MQW devices with silica glass dielectric layers.[1] These devices were fabricated using substrate thinning techniques. In our structure, conduction of the trapped carriers across the 30-nm-thick LT AlGaAs layers into the metal electrodes likely reduced the fringe visibility, thereby lowering the η. In order to reduce carrier conduction, a 80-nm-thick nitride layer was deposited by plasma-enhanced chemical vapor deposition (CVD) between the top electrode and the LT layer in another device fabricated using ELO from the same epitaxial material. More than two orders of magnitude reduction in the leakage current density was observed over the entire bias range, and a significantly higher η of 0.5% was obtained. Thicker and/or wider band gap LT AlGaAs layers may similarly improve carrier confinement,[16] resulting in a high η.

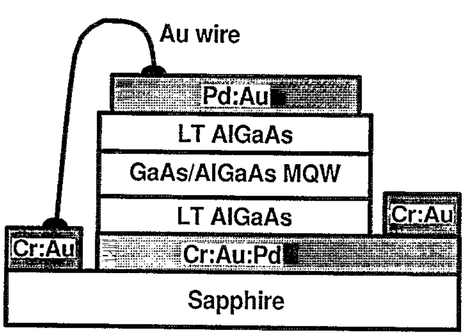

FIG. 2. Schematic cross section of the MQW resonant photorefractive device.

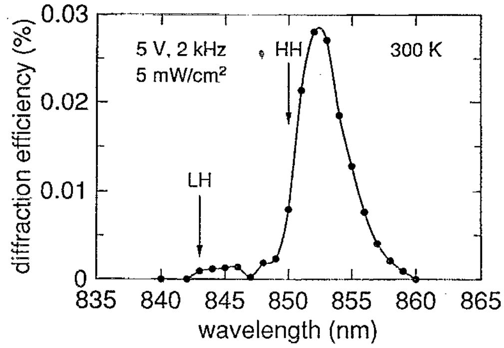

FIG. 3. Diffraction efficiency as a function of wavelength. The LH and HH exciton peak positions are indicated for the unbiased device.

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